Testing of Shipboard Power Systems: A Case for Remote Testing and Measurement

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Abstract: Five universities have teamed up to develop *R*emote *T*esting and *M*easurement (RTM) strategies and devices to interconnect power system laboratories for advanced, non-destructive testing and measurement of power systems. The aim is to create a large-scale power system laboratory that will be virtually connected via the internet and the RTMs. Through such technology, methodologies for testing and debugging shipboard power systems can be achieved and repeated. Several experiments can be developed utilizing a mix of hardware and software capabilities at each individual university. This paper will highlight our initial efforts in the areas of collaboration, modeling, communications and software implementations.

Keywords: remote testing, remote experiments, measurement, power hardware, power simulations

I. INTRODUCTION

Naval shipboard power systems have greatly evolved from the first shipboard electric generation/distribution application on the USS Trenton in 1883 which supplied 247 lamps at 110VDC with a single dynamometer. The power demand on the ship has evolved from kilowatts to tens of megawatts, and is constantly increasing with new ship designs and concepts. One particular concept affecting directly the shipboard power system is the vision for an All Electric Ship, which signifies the move of the shipboard power system from an electromagnetic/electromechanical basis to a power electronic basis [1,2].

Shipboard power systems are unique in their composition, and differ from terrestrial systems in many ways:

- Fast turbine governors have to maintain system frequency
- Time constants of the generators are closer to the electrical time constants than in terrestrial systems, meaning the systems are not necessarily stiff
- Generator loads are not scheduled
- Large dynamic loads consume a large portion of the generation capacity
- Ungrounded systems using delta-configured loads allow for continued operation in the case of single-phase faults
- Transmission line dynamics are limited due to the length of the ship and the selected distribution topology
- System reconfiguration routines [3] are much faster and a large portion of the system load is sensitive to power interruptions. A small interruption of approximately 100 ms. can cause subsystems to shut-down.
- Redundancy is incorporated in all aspects of system design to ensure survivability

When distributed resources including hardware and software components that make up various components critical to a shipboard power system are present, there is always need to perform various tests on them. These tests are used for verification, validation and specification purposes to name a few. Presently, tests are accomplished on both a device-level and a system-level basis. With respect to the latter, there is a need to develop a scaled-up facility to house the various components and interconnect them in the form of actual shipboard power system configurations. It goes without saying that enormous time and manning is necessary to accomplish this goal for only the purposes of testing and measurement. Another option exists: Remote Testing and Measurement.

To address this, five universities in the US have teamed up to develop *R*emote *T*esting and *M*easurement (RTM) devices to interconnect power system laboratories for advanced, non-destructive testing and measurement of power systems. The aim is to create a large-scale power system laboratory that will be virtually connected via the internet and the RTMs. Several implementations of the interconnections could be achieved and a conceptual diagram of remote software to hardware power system setups is shown in Figure 1 on the following page. This concept is a second stage

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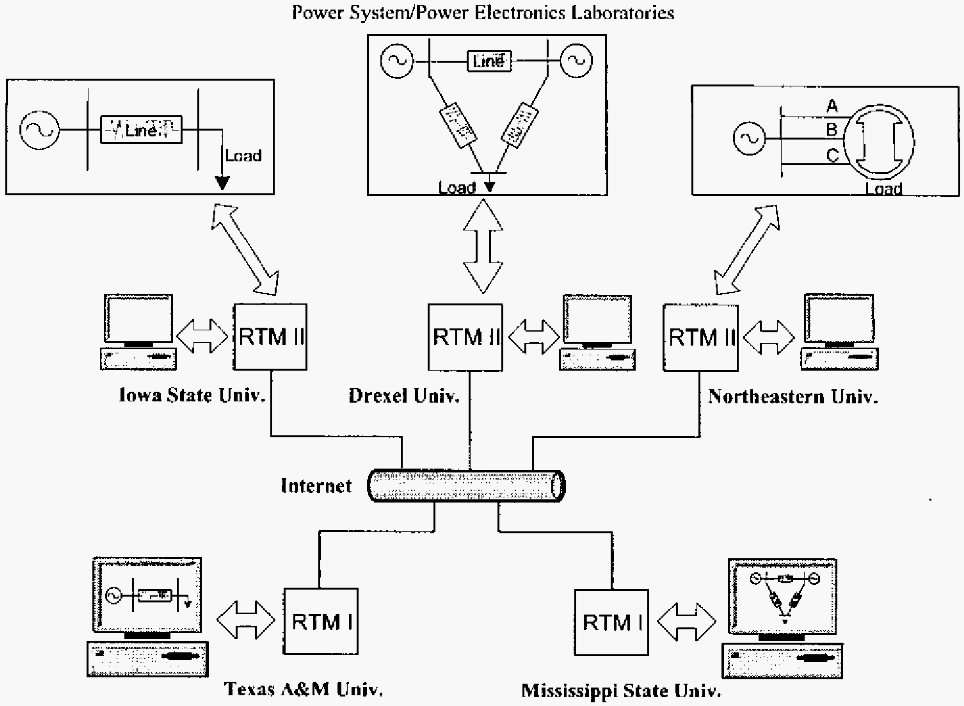

Figure 1. Conceptual Remote Testing and Measurement Setup Between Participating Universities

demonstration where simulation models and hardware equipment at various locations can be combined for advanced experimentation.

Consequently, the effects of communication delays, control device limitations, computation difficulties, to name a few, can be studied under such a platform and various power system configurations can be developed and verified using actual, easily accessible, measured data. The work includes:

- Power system sensing and signal conditioning
- Development of controllable loads, including converter technologies
- Development of remote measurement and testing techniques and models

The work is expected to have significant impacts on:

- Signal conditioning devices
- The way electric power systems are monitored, modeled, controlled and analyzed
- A new generation of power engineers who understand measurement design and its relationships to hardware component analysis, mathematical modeling and analysis of shipboard power systems.

In addition, the work can also extend to testing of terrestrial and other power systems.

In terms of work to be reported in this paper, towards the development of the RTMs, we report various aspects of RTMs and their integration to perform interconnected power system experiments under electrically stressed conditions and a controlled and measurable environment. For larger system studies, hardware power systems need to be connected to virtual power systems and other remote hardware power systems via a communication link. Testing procedures and measurement capabilities will be tailored for shipboard power systems.

Five desired remote interconnections and experiments are under consideration:

- Implementation I: software power simulation tools to software power simulation tools
- Implementation II: software power simulation tools to hardware power systems
- Implementation III: hardware power systems to hardware power systems
- Implementation IV: software power simulation tools to multiple hardware systems
- Implementation V: multiple interconnected hardware/software power systems

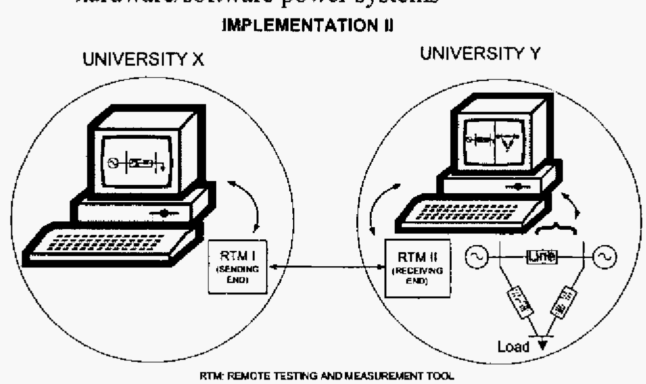

Figure 2. Implementation II: Software Power System (Univ. X) — Hardware Power System Setups (Univ. Y)

The main objectives to achieve the remote interconnections and experiments include the following:

- Development of RTM I for software interconnections

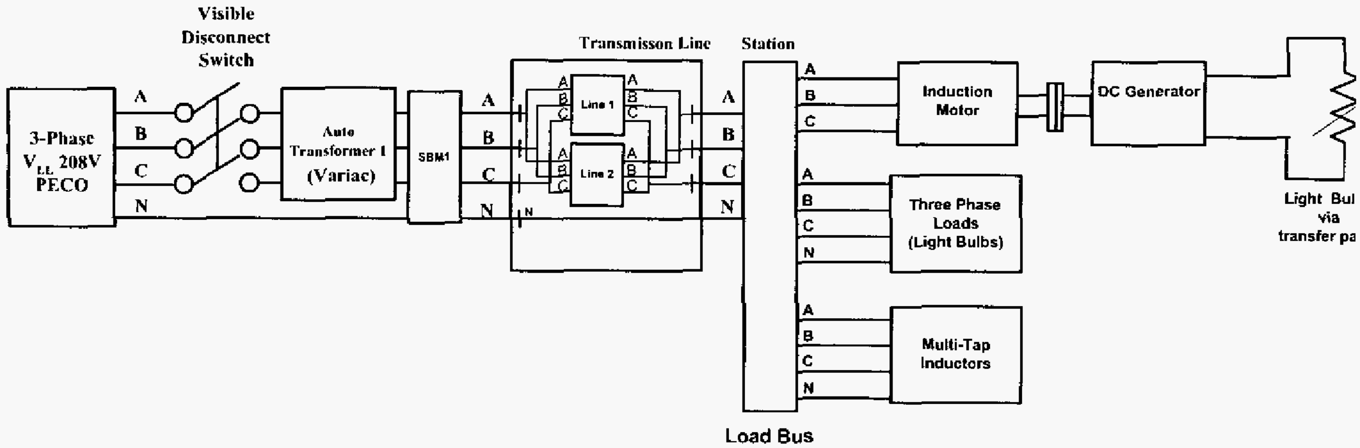

Figure 3. Sample hardware system which can be created within Drexel's Interconnected Power System Laboratory (IPSL) [4]

Table 1 Average Impedance of Multi-tap Transmission Line Reactors

	Reactor Tap Setting (Ohm)						
Reactor #	0.5	1	2	3	6	12	24
17	0.13+j0.6	0.17+j1.11	0.34+j2.18	0.5+j3.23	0.67+j6.48	1.34+j12.85	2.67+j25.27
18	0.16+j0.58	0.23+j1.08	0.37+j2.16	0.45+j3.16	0.72+j6.38	1.29+j12.66	2.53+j25.16
19	0.14+j0.6	0.19+j1.13	0.36+j2.22	0.41+j3.27	0.69+j6.61	1.34+j13.11	2.59+j25.79

Table 2 Average Resistance of Resistive Loads (80 W 120 V Carbon Filament Light Bulbs)

# of Light Bulbs in parallel	5	10	20	30	40	50	60
R (Ohm)	41.808	22.726	12.934	8.9825	7.10625	5.88125	5.035

- Development of RTM II for hardware interconnections
- Development of experimental setups and non-destructive test procedures of power system phenomena under each implementation.

We note that our initial focus has been on the first two implementations. In addition, the types of experiments to be included will focus on achieving nondestructive testing by driving these systems beyond normal operating conditions. This will allow researchers to investigate power system and component behavior on the verge of impending collapse without actually destroying the hardware involved and not adversely affecting the surrounding environment. Hence, the element of safety will permeate throughout the proposed device development.

Towards this end, three universities: Drexel University, Northeastern University and Iowa State University, have agreed to allow remote access to their power hardware laboratories. Two universities, Texas A&M University and Mississippi State University, participate through model and software development and performance evaluations of remote measurement and testing of the hardware laboratories. In association with these laboratories, several experiments can be developed utilizing a mix of hardware capabilities at each individual university. This paper will highlight our initial efforts in the areas of collaboration, modeling, communications and software implementations.

The paper is organized as follows: in Section II, the physical setup of one hardware labortory is presented. Preliminary modeling and communication selections are given in Section III. Finally in Section IV, two remote software experiments, one investigating maximum power transfer limits are illustrated in detail and ongoing and future work test results are discussed.

II. LABORATORY OVERVIEW

The electric power system and power electronics hardware laboratories at three universities will be utilized for establishing RTMs. Each university laboratory brings different hardware capabilities. In this paper, we highlight one example of laboratory capabilities. Specifically, a typical set-up which can be implemented in Drexel University's Interconnected Power System Laboratory (IPSL) is shown in Figure 3. Averaged parameters of select components, used in the following sections, are displayed in Tables 1 and 2. Other component parameter values can be obtained from [5]. This setup can be created both in hardware and software and is the basis for our preliminary RTM designs.

III. MODELING & COMMUNICATION

Several shipboard power system modeling issues arise to enable remote interconnections of software simulations to other software simulations and to other hardware components. The initial work presented in this paper addresses issues regarding the multi-phase modeling of power systems required to represent shipboard power systems. Towards this end, three modeling procedures and tools have been investigated.

First, using, SimPower a toolbox within Mathworks Matlab Simulink, static multi-phase line models and discretely controllable loads have been built. For example, a two bus power system model was created using SimPower, representing hardware currently available in IPSL from Figure 3. The model consists of a three phase voltage source, three phase transmission line, and (3) three phase RLC loads seen in Figure 4.

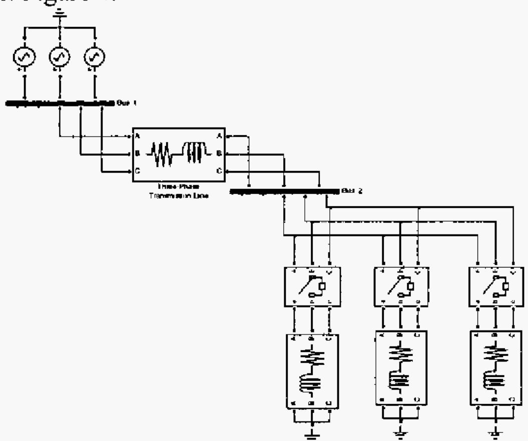

Figure 4: Two-Bus Power System Model Based on IPSL

To enable richer power system models, the Matlab programming language has been used to model unbalanced, ungrounded and delta connected power system components. Here, since delta connections and ungrounded systems, do not include a separate reference phase, the application of traditional three-phase component models can lead to singularity problems in system analysis tools. To avoid potential ill-conditioning, component and system models constructed on line-to-line voltages can be used [7, 8]. In addition, the use of line-to-line voltages can be related to actual voltage measurements taken onboard shipboard systems and across delta connected hardware.

For example, at bus k, there exists the voltage V_k and injected current I_k. For a three-phase bus in a four-wire section of the network they are

$$V_k = \begin{bmatrix} V_k^a \\ V_k^b \\ V_k^c \end{bmatrix} \quad \text{and} \quad I_k = \begin{bmatrix} I_k^a \\ I_k^b \\ I_k^c \end{bmatrix} \qquad (3)$$

This leads to the standard Y_{bus} formulations for solving multi-phase power systems. Standard representations of network devices connected at bus k, for example SimPower, can therefore be used without modification.

However, if bus k is a three-phase ungrounded bus with delta connected loads, voltage and current can be given by

$$V_k = \begin{bmatrix} V_k^{ab} \\ V_k^{bc} \end{bmatrix} \quad \text{and} \quad I_k = \begin{bmatrix} I_k^a \\ I_k^b \end{bmatrix} \qquad (4)$$

Use of the line-to-line voltage and the reduced dimension current requires corresponding modifications to the standard representations of the network devices connected at bus k. The modifications to the component model representations imply a modified Y_{bus}. for system solvers, [7,9].

Another modeling platform under investigation is the Virtual Test Bed [10], VTB, a powerful multidisciplinary simulation tool including electrical, mechanical, chemical and thermal engineering. Ongoing work is extending single phase connection models to enable multi-phase connection models and develop a controllable load model in VTB. This will increase the suitability for its application to RTM development with eventual connections to three-phase power hardware.

Finally, remote testing and measurement will also require a stable communication system. As such, we have selected the use of TCP/IP for the communication backbone. Several standard software packages utilize these protocols and provide TCP/IP communication modules. Specifically, LabVIEW and its embedded TCP/IP capabilities have been selected for initial software implementations in this work [11].

IV. SOFTWARE IMPLEMENTATIONS

Several software implementations have been developed to perform remote testing and measurement under varying degrees. These design alternatives are currently under investigation for achieving remote testing and measurement of software simulations (RTM I). They include:

- LabVIEW Simulation Interface Toolkit & Simulink
- LabVIEW Matlab Script Node, Active X and Matlab
- VTB

Our initial efforts utilized off-the-shelf products such as LabVIEW, its Simulation Interface Toolkit (SIT) and Matlab Simulink. The results are discussed in this paper. Results from other software implementations have also been obtained, but are not shown in this paper.

Advantages of the initial implementation are the use of commercially available products that are easiliy disseminated to multiple sites. In addition, with its facilitated connections to hardware devices, the use of LabVIEW provides insight for the development of RTM II. While this method of software to software implementations is straightforward, limitations of this method will be discussed later in this section.

The Simulation Interface Toolkit (SIT), facilitates the creation of remote interfaces to control and monitor Matlab Simulink. Utilizing this toolkit along with the developed power system models, controls were created which are capable of handling the execution of a Simulink simulation. In addition, system parameters and measurements were mapped to control boxes and indicators on the interface. The

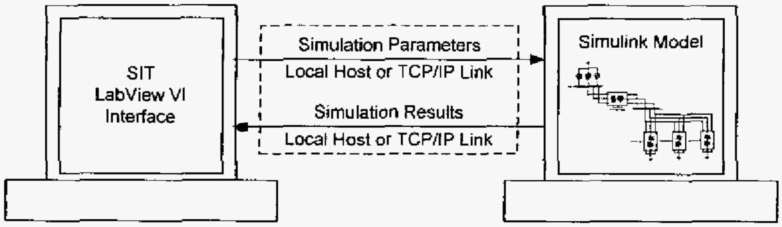

Figure 5: Remote SIT System Architecture

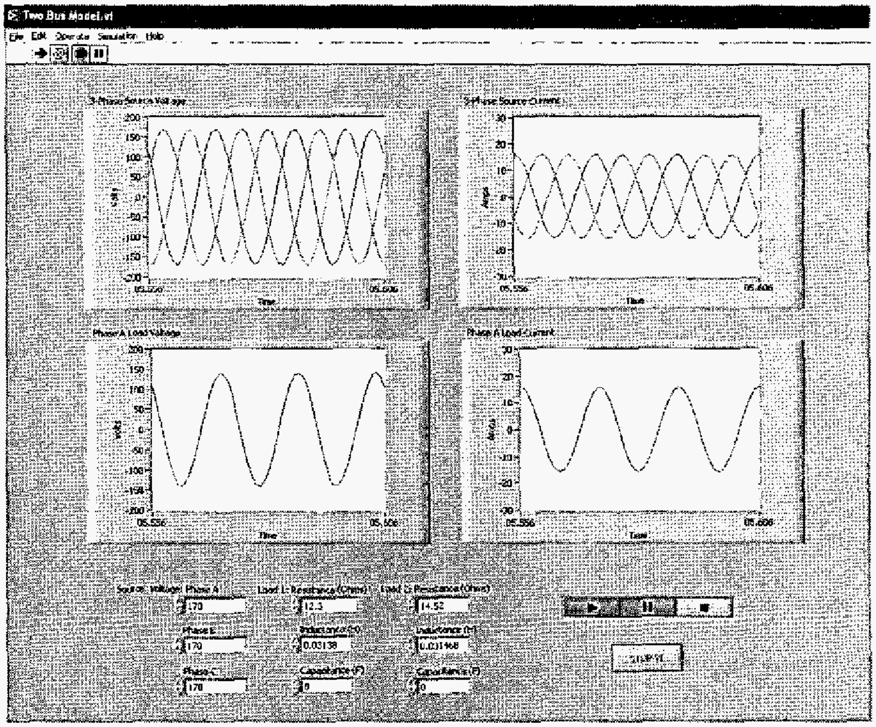

Figure 6: Remote Two-Bus Power Flow Interface

interface can then be run remotely utilizing TCP/IP communication to connect with a host computer running the Simulink simulation. Figure 5 presents an overview of the remote SIT system architecture.

Through this manner, the remote control and monitoring of power system simulations has been implemented by all universities involved in the project. Under this structure, two experiments were developed. The first experiment evaluated power system performance under normal operating conditions. The second experiment evaluated power system performance under stressed loading conditions.

IV. 1. AC Power Flow Loading Experiments

In this experiment, the two bus power system model from Figure 4 was created in Simulink using SimPower component blocks. On/off switches were incorporated to discretely control all phases of a load at one time. After the model was completed an SIT interface was then created with indicators to monitor the source bus voltages, load bus voltages and currents entering the load bus. In addition, controls to vary the source voltage magnitude and the RLC parameters of loads were included. Additional measurements on the source bus can also be added.

In this implementation, one computer hosts the SimPower simulation while the interface was run at another, remote university. The following procedure is described with Drexel as the host and ISU as the remote university running the interface. Please note that the experiment has been repeated between multiple pairs of all participating universities.

A student at ISU, the remote university, then controlled and monitored the simulation running at Drexel University. This involved changing parameters either voltage source magnitudes and/or RLC load parameters and monitoring the system response. Figure 6 shows the remote interface along with results from this experiment as seen by Iowa State University. The top 2 waveforms are the 3ϕ measured source voltages and currents; the bottom 2 waveforms are the phase A (arbitrarily chosen) measured load voltage and current; text boxes at the bottom are control inputs for ABC source voltage magnitudes and for RLC parameters of each balanced load.

IV. 2 . Maximum Power Flow Experiments

A remote simulation was developed to investigate the maximum power flow limits for systems consisting of a three phase voltage source, three phase transmission line, and varying resistive load. The system model was created using SimPower as seen in Figure 7. Selected base parameters model hardware currently available in IPSL.

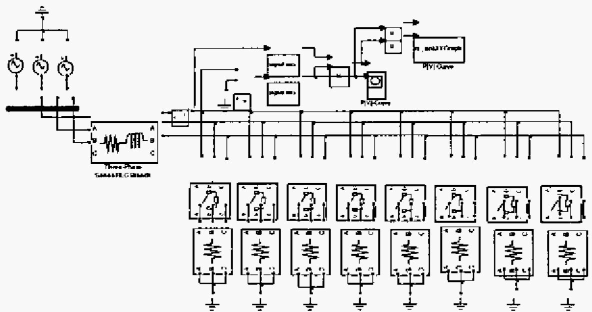

Figure 7: System Model for Maximum Power Transfer Studies

An SIT interface was created to monitor voltage and current measurements and to create a P|V| curve of the system. Controls were created to adjust the three phase source voltage magnitude and transmission line RL parameters to study the sensitivity of maximum power transfer to different transmission line taps. Here, load increases were controlled sequentially by a timer.

Again, while these simulations can be performed by various universities, the discussion will be described with respect to ISU and Drexel. The simulation was hosted on an ISU computer with the interface running remotely at DU. A student at DU then controlled the simulation, changing transmission line parameters and source voltage magnitude, to observe resulting P|V| curves of the system. The SIT interface including results from the experiment is shown in Figure 8. The resulting phase A P|V| curve is plotted. Text boxes at the bottom are control inputs for ABC source voltage magnitudes and for balanced transmission line RL parameters.

The above experiments have demonstrated the remote control and monitoring of power system simulations. The remote simulations were implemented successfully across all schools involved in the project. It is noted that these experiments have limitations such as their ability to handle only one simulation and the manual interaction required to alter simulation parameters; however, as an initial step the exercise of performing these experiments has proven beneficial by exposing current safe guards which prohibit data transfers between universities. Through this process open data transfer and communication has been facilitated between all participating universities.

Ongoing work includes the adoption of LabVIEW with embedded Matlab programming code. This will provide the ability to adopt more detailed power system modeling and the ability to perform multiple, remote starts of power system simulations. In addition, remote experiments of single-phase systems in VTB have been achieved and current work involves the extension of models to multi-phase.

Finally, some nontrivial considerations towards the development of RTM devices are now discussed. This paper summarizes initial work and results in the process of achieving remote testing and measurement of software to software interconnections. A significant area of ongoing research involves the real-time simulation for the software portions of the virtually connected power system. In addition, communication and simulation delays must be accounted for and modeled in power system models to be used for remote testing. The team will acquire GPS timer boards to build stochastic models for the time delays. Related to this is the need to establish the required data models and rate of data to be passed between remote locations.

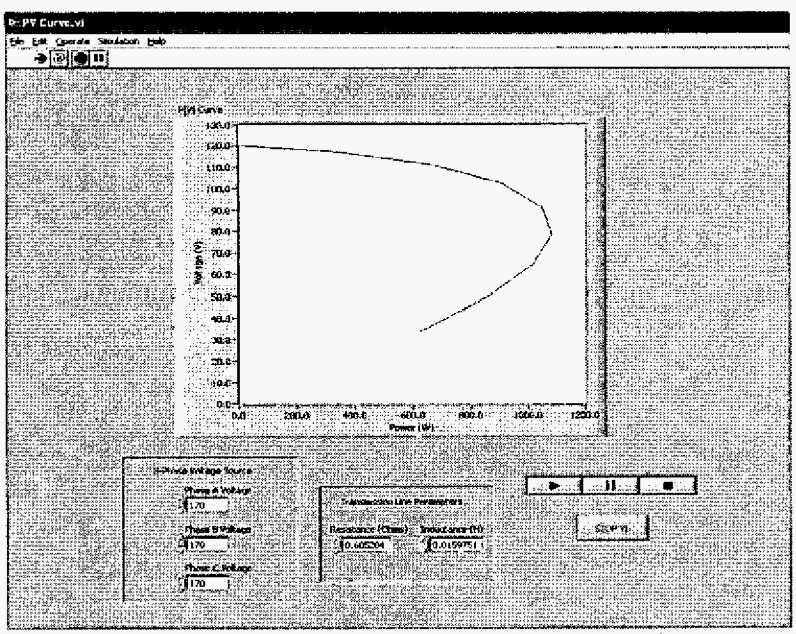

Figure 8: Maximum Power Flow Experiment Interface

We note that equivalent stand-alone hardware experiments have been achieved within the power system laboratories at both Drexel and ISU. However, software to hardware interconnections will require the development and proper modeling of automated control devices both in time and space. In addition, careful study of the measurement devices themselves including signal conditioning, self calibration capabilities, sampling rates and data windows is needed.

V. CONCLUSIONS

In this paper, a procedure for establishing remote testing and measurement of power systems has been outlined. Five universities are collaborating to establish requirements for building remote testing and measurement devices to allow for large power system hardware and software simulations.

Specific examples and parameters of an existing hardware power system laboratory were provided. Then both standard and emerging models for power systems which contain multiple connection types (Y or Δ) were identified. The existing sample system was then modeled and successfully implemented into an initial architecture for remote testing and measurement of software simulations.

Completion of this project will provide an alternative method for the nondestructive testing of shipboard power systems. In addition, it will establish procedures to develop devices to allow remote naval laboratories to interconnect and perform larger system studies.

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VII. REFERENCES

[1] National Research Council, Technology for the United States Navy and Marine Corps 2000-2035-Becoming a 21st Century Force, Volume 2: Technology, National Academic Press, Washington, 1997.

[2] H. Hegner, B. Desai, "Integrated Fight Through Power", *IEEE Power Engineering Society Summer Meeting Proceedings*, Vol.1, July 2002, pp 336-339.

[3] K. L. Butler, N. D. R. Sarma, V. Prasad, "Network Reconfiguration for Service Restoration in Shipboard Power Distribution Systems"; *IEEE Trans. On Power Systems*, vol. 16, no. 4, Nov, 2001, pp. 653-661.

[4] S. P. Carullo, et al, "Interconnected Power System Laboratory: Fault Analysis Experiment," *IEEE Trans. on Power Systems*, Vol. 11, No. 4, November 1996, pp. 1913-1917..

[5] X. Yang, C. Bruni, D. Cheung, Y. Mao, G. Sokol, K. Miu, C. Nwankpa, "Setup of RDAC - A Reconfigurable Distribution Automation and Control Laboratory", *Proceedings of the IEEE Power Engineering Society Summer Meeting*, Vol. 3, Vancouver, CAN, July 2001, pp. 1524-1529.

[6] S. Ayasun, R. Fischl, T. Chmielewski, S. Vallieu, K. Miu, C. Nwankpa, "Evaluation of the Static Performance of a Simulation-Stimulation Interface for Power Hardware in the Loop," *Proceedings of the 2003 PowerTech Conference*, Bologna, Italy, June, 2003.

[7] R. D. Zimmerman, "Comprehensive Distribution Power Flow: Modeling, Formulation, Solution Algorithms and Analysis," Ph.D. Dissertation, Cornell University, 1995.

[8] R. Zimmerman, H.-D. Chiang and K. N. Miu, "Transformer Modeling Using Line-to-Line Voltages," *Proceedings of the IEEE PES Transmission & Distribution Conference*, Dallas, TX, Sept. 2003.

[9] K. N. Miu and H.-D. Chiang, "Existence, Uniqueness and Monotonic Properties of the Feasible Power Flow Solution for Radial Three-Phase Distribution Networks," *IEEE Transactions on Circuits and Systems*, Vol. 47, No. 10, Oct. 2000, pp. 1502-1514.

[10] Proceedings of the VTB Users Workshop, Sept. 2003.

[11] National Instruments, "LabVIEW User Manual," 2004.